

## CLAIMS

What is claimed is:

1. An optical apparatus, comprising:
  - a semiconductor device substrate;
  - a semiconductor optical device formed on the device substrate and including a device waveguide segment terminating at a device end face; and
  - an end-coupled planar optical waveguide formed on the device substrate at the device end face and end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide including a waveguide core and waveguide cladding,wherein a proximal portion of the end-coupled waveguide includes at least one of
  - a) waveguide cladding material between the device end face and a proximal end of the waveguide core, and
  - b) waveguide core material on the device end face extending upward from the waveguide core away from the substrate.
2. The apparatus of Claim 1, wherein the proximal portion of the end-coupled waveguide includes waveguide cladding material between the device end face and the proximal end of the waveguide core.
3. The apparatus of Claim 2, wherein the waveguide cladding material between the device end face and the proximal end of the waveguide core results in a proximal segment of the end-coupled waveguide lacking substantially complete transverse optical confinement.
4. The apparatus of Claim 2, wherein the waveguide cladding material between the device end face and the proximal end of the waveguide core forms a multimode waveguide segment.
5. The apparatus of Claim 4, wherein the waveguide core supports an optical mode substantially spatial-mode-matched with an optical mode supported by the device waveguide segment, and the length of the multimode waveguide segment is chosen so as to result in substantially spatial-mode-matched end-coupling between the

1 device waveguide segment and the portion of the end-coupled waveguide that  
2 includes the waveguide core.

3 6. The apparatus of Claim 4, wherein the waveguide core supports an optical mode  
4 larger than an optical mode supported by the device waveguide segment, and the  
5 length of the multimode waveguide segment is chosen so that it functions as a  
6 mode expander for end-coupling the device waveguide segment and the end-  
7 coupled waveguide.

8 7. The apparatus of Claim 2, wherein:  
9 the proximal portion of the end-coupled waveguide includes waveguide core  
10 material extending upward from the waveguide core away from the substrate;  
11 the proximal portion of the end-coupled waveguide includes waveguide cladding  
12 material between the device end face and the upwardly-extending waveguide  
13 core material; and  
14 the thickness of the waveguide cladding material between the device end face and  
15 the upwardly-extending waveguide core material is chosen to alter an effective  
16 reflectivity of the device end face.

17 8. The apparatus of Claim 1, wherein the proximal portion of the end-coupled  
18 waveguide includes waveguide core material on the device end face extending  
19 upward from the waveguide core away from the substrate.

20 9. The apparatus of Claim 1B, wherein the waveguide core material on the device end  
21 face results in a proximal segment of the end-coupled waveguide lacking  
22 substantially complete transverse optical confinement, and the waveguide segment  
23 lacking substantially complete optical confinement is less than about 1  $\mu\text{m}$  long.

24 10. The apparatus of Claim 1, wherein the end-coupled waveguide comprises a low-  
25 index planar optical waveguide.

26 11. The apparatus of Claim 1, further comprising a reflective coating formed between  
27 the device substrate and at least a portion of the end-coupled waveguide.

12. The apparatus of Claim 1, further comprising an optical coating formed between the device end face and the end-coupled waveguide.
13. The apparatus of Claim 1, further comprising a second optical waveguide optically end-coupled with the end-coupled planar optical waveguide at a distal end thereof.
14. The apparatus of Claim 1, further comprising a second optical waveguide optically transverse-coupled with the end-coupled planar optical waveguide.
15. The apparatus of Claim 1, wherein the end-coupled waveguide includes a dual-core segment.
16. The apparatus of Claim 1, wherein at least a portion of the device end face is curved in at least one dimension.
17. The apparatus of Claim 1, wherein the device end face is non-normal with respect to optical propagation along the device waveguide segment.
18. The apparatus of Claim 1, wherein:  
the device end face includes an outwardly protruding portion extending along the substrate from a bottom portion of the device end face beneath a proximal portion of the end-coupled waveguide; and  
at least one layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing layer thickness together yielding a desired layer surface profile for at least one layer of the end-coupled waveguide.
19. The apparatus of Claim 1, wherein the device waveguide segment functions as a transverse-mode expander.
20. The apparatus of Claim 1, further comprising:  
a second device waveguide segment of the semiconductor optical device terminating at a second device end face; and

1 a second end-coupled planar optical waveguide formed on the device substrate at  
2 the second device end face and end-coupled at its proximal end to the device  
3 waveguide through the second device end face, the second end-coupled  
4 waveguide including a waveguide core and waveguide cladding,  
5 wherein the proximal end of the second end-coupled waveguide includes at least  
6 one of a) waveguide cladding material between the second device end face  
7 and a proximal end of the waveguide core of the second end-coupled  
8 waveguide, and b) waveguide core material on the second device end face  
9 extending upward from the waveguide core of the second end-coupled  
10 waveguide away from the substrate.

11 21. An optical apparatus, comprising:

12 a semiconductor device substrate;

13 a semiconductor optical device formed on the device substrate and including a  
14 device waveguide segment terminating at a device end face; and

15 an end-coupled planar optical waveguide formed on the device substrate at the  
16 device end face and end-coupled at its proximal end to the device waveguide  
17 through the device end face, the end-coupled waveguide including a waveguide  
18 core and waveguide cladding; and

19 a reflective coating formed between the device substrate and at least a portion of  
20 the end-coupled waveguide.

21 22. The apparatus of Claim 21, wherein the reflective coating comprises a metallic  
22 coating.

23 23. The apparatus of Claim 21, wherein the reflective coating comprises a dielectric  
24 coating.

25 24. The apparatus of Claim 21, wherein the end-coupled waveguide comprises a low-  
26 index planar optical waveguide.

27 25. An optical apparatus, comprising:

28 a semiconductor device substrate;

1 a semiconductor optical device formed on the device substrate and including a  
2 device waveguide segment terminating at a device end face; and  
3 an end-coupled planar optical waveguide formed on the device substrate at the  
4 device end face and end-coupled at its proximal end to the device waveguide  
5 through the device end face, the end-coupled waveguide including a waveguide  
6 core and waveguide cladding; and  
7 a second optical waveguide optically end-coupled with the end-coupled planar  
8 optical waveguide at a distal end thereof.

9 26. The apparatus of Claim 25, wherein the second optical waveguide comprises an  
10 optical fiber mounted on the device substrate.

11 27. The apparatus of Claim 25, wherein the second optical waveguide comprises a  
12 planar optical waveguide formed on a waveguide substrate with the device  
13 substrate mounted on the waveguide substrate.

14 28. The apparatus of Claim 25, wherein the end-coupled waveguide functions as a  
15 transverse-mode expander.

16 29. The apparatus of Claim 25, wherein the end-coupled waveguide comprises a low-  
17 index planar optical waveguide.

18 30. An optical apparatus, comprising:

19 a semiconductor device substrate;

20 a semiconductor optical device formed on the device substrate and including a  
21 device waveguide segment terminating at a device end face; and

22 an end-coupled planar optical waveguide formed on the device substrate at the  
23 device end face and end-coupled at its proximal end to the device waveguide  
24 through the device end face, the end-coupled waveguide including a waveguide  
25 core and waveguide cladding; and

26 a second optical waveguide optically transverse-coupled with the end-coupled  
27 planar optical waveguide.

- 1 31. The apparatus of Claim 30, wherein the second optical waveguide comprises a  
2 planar optical waveguide formed on a waveguide substrate with the device  
3 substrate mounted on the waveguide substrate.
- 4 32. The apparatus of Claim 30, wherein transverse-coupling between the end-coupled  
5 waveguide and the second waveguide is substantially adiabatic transverse-  
6 coupling.
- 7 33. The apparatus of Claim 30, wherein the end-coupled waveguide comprises a low-  
8 index planar optical waveguide.
- 9 34. An optical apparatus, comprising:  
10 a semiconductor device substrate;  
11 a semiconductor optical device formed on the device substrate and including a  
12 device waveguide segment terminating at a device end face; and  
13 an end-coupled planar optical waveguide formed on the device substrate at the  
14 device end face and end-coupled at its proximal end to the device waveguide  
15 through the device end face, the end-coupled waveguide including a waveguide  
16 core and waveguide cladding,  
17 wherein at least a portion of the device end face is curved in at least one dimension.
- 18 35. The apparatus of Claim 34, wherein the curved portion of the end face is convex.
- 19 36. The apparatus of Claim 34, wherein the curved portion of the end face serves to  
20 increase reflective optical coupling of a device optical mode back into the device  
21 waveguide segment, relative to a substantially flat device end face.
- 22 37. The apparatus of Claim 34, wherein the curved portion of the end face serves to  
23 increase optical end-coupling between the device waveguide segment and the end-  
24 coupled waveguide, relative to a substantially flat device end face.
- 25 38. The apparatus of Claim 34, wherein the curved portion of the end face is limited in  
26 transverse extent so as to suppress higher-order device optical modes.

1 39. The apparatus of Claim 34, wherein the end-coupled waveguide comprises a low-  
2 index planar optical waveguide.

3 40. An optical apparatus, comprising:

4 a semiconductor device substrate;

5 a semiconductor optical device formed on the device substrate and including a  
6 device waveguide segment terminating at a device end face; and

7 an end-coupled planar optical waveguide formed on the device substrate at the  
8 device end face and end-coupled at its proximal end to the device waveguide  
9 through the device end face, the end-coupled waveguide including a waveguide  
10 core and waveguide cladding,

11 wherein:

12 the device end face includes an outwardly protruding portion extending along the  
13 substrate from a bottom portion of the device end face beneath a proximal  
14 portion of the end-coupled waveguide; and

15 at least one layer of the end-coupled waveguide decreases in thickness toward the  
16 end face, the outwardly protruding portion of the device waveguide and the  
17 decreasing layer thickness together yielding a desired layer surface profile for at  
18 least one layer of the end-coupled waveguide.

19 41. The apparatus of Claim 40, wherein a lower cladding layer of the end-coupled  
20 waveguide decreases in thickness toward the end face, the outwardly protruding  
21 portion of the device waveguide and the decreasing lower cladding layer thickness  
22 together yielding a substantially flat upper surface of the lower cladding layer above  
23 the protruding portion of the device waveguide.

24 42. The apparatus of Claim 40, wherein a lower cladding layer of the end-coupled  
25 waveguide decreases in thickness toward the end face, the outwardly protruding  
26 portion of the device waveguide and the decreasing lower cladding layer thickness  
27 together serving to position a proximal end of a core of the end-coupled waveguide  
28 for optical end-coupling with the optical device.

1 43. The apparatus of Claim 40, wherein the end-coupled waveguide comprises a low-  
2 index planar optical waveguide.

3 44. A method, comprising:

4 forming a semiconductor optical device on a device substrate, the optical device

5 including a device waveguide segment terminating at a device end face;

6 depositing waveguide cladding material on the substrate and the device end face so

7 that the cladding material substantially covers the device end face and forms a  
8 waveguide lower cladding layer;

9 depositing waveguide core material over the lower cladding layer so as to form a

10 waveguide core, deposited waveguide core material extending upward from a

11 proximal end of the waveguide core away from the substrate; and

12 depositing waveguide cladding material over the waveguide core material and lower

13 cladding layer so as to form a waveguide upper cladding layer,

14 wherein the lower cladding layer, the waveguide core, and the upper cladding layer

15 form an end-coupled planar optical waveguide on the device substrate end-

16 coupled at its proximal end to the device waveguide through the device end

17 face.

18 45. The method of Claim 44, wherein multiple optical devices are formed concurrently  
19 on a common device substrate wafer, and multiple corresponding end-coupled  
20 waveguides are formed concurrently on the common substrate wafer, and further  
21 comprising dividing the common substrate wafer into multiple device substrates.

22 46. The method of Claim 44, wherein the proximal portion of the end-coupled  
23 waveguide includes waveguide cladding material between the device end face and  
24 the proximal end of the waveguide core.

25 47. The method of Claim 46, further comprising forming a multimode waveguide  
26 segment from the cladding material between the device end face and the proximal  
27 end of the waveguide core.

28 48. The method of Claim 46, wherein:



1 the proximal portion of the end-coupled waveguide includes waveguide cladding  
2 material between the device end face and the upwardly-extending waveguide  
3 core material; and  
4 the thickness of the waveguide cladding material between the device end face and  
5 the upwardly-extending waveguide core material is chosen to alter an effective  
6 reflectivity of the device end face.

7 49. The method of Claim 44, wherein the proximal portion of the end-coupled  
8 waveguide includes waveguide core material on the device end face extending  
9 upward from the proximal end of the waveguide core away from the substrate.

10 50. The method of Claim 49, wherein the waveguide core material on the device end  
11 face results in a proximal segment of the end-coupled waveguide lacking complete  
12 transverse optical confinement, the waveguide segment lacking complete optical  
13 confinement being less than about 1  $\mu\text{m}$  long.

14 51. The method of Claim 49, further comprising, before depositing the waveguide core  
15 material:  
16 masking the lower cladding layer, leaving unmasked that portion of the waveguide  
17 cladding material covering the device end face;  
18 forming a substantially flat upper surface of the lower cladding layer and exposing  
19 an upper portion of the device end face by removing the unmasked portion of  
20 the waveguide cladding material until it is about the same thickness as the  
21 lower cladding layer and thereby forms a portion thereof; and  
22 de-masking the lower cladding layer,  
23 wherein the upward-extending waveguide core material at the proximal end of the  
24 waveguide core is deposited on the exposed upper portion of the device end  
25 face.

26 52. The method of Claim 49, wherein waveguide cladding material deposited on the  
27 device substrate and on the device end face is at least as thick as the device  
28 waveguide segment, and further comprising, before depositing waveguide core  
29 material:

1 forming a substantially flat waveguide cladding material upper surface substantially  
2 flush with an upper surface of the device waveguide segment by removing  
3 waveguide cladding material by chemical-mechanical polishing; and  
4 forming a substantially flat lower cladding layer and exposing an upper portion of  
5 the device end face by removing waveguide cladding material by cladding-  
6 material-specific etching,  
7 wherein the upward-extending waveguide core material at the proximal end of the  
8 waveguide core is deposited on the exposed upper portion of the device end  
9 face.

10 53. The method of Claim 44, wherein the end-coupled waveguide comprises a low-  
11 index planar optical waveguide.

12 54. The method of Claim 44, further comprising forming a reflective coating between the  
13 device substrate and at least a portion of the end-coupled waveguide.

14 55. The method of Claim 44, further comprising forming an optical coating between the  
15 device end face and the end-coupled waveguide.

16 56. The method of Claim 44, further comprising optically end-coupling a second optical  
17 waveguide with the end-coupled planar optical waveguide at a distal end thereof.

18 57. The method of Claim 44, further comprising optically transverse-coupling a second  
19 optical waveguide with the end-coupled planar optical waveguide.

20 58. The method of Claim 44, wherein the end-coupled waveguide includes a dual-core  
21 segment.

22 59. The method of Claim 44, wherein at least a portion of the device end face is curved  
23 in at least one dimension.

24 60. The method of Claim 44, wherein the device end face is non-normal with respect to  
25 optical propagation along the device waveguide segment.

1 61. The method of Claim 44, further comprising adapting the device waveguide  
2 segment for functioning as a transverse-mode expander.

3 62. The method of Claim 44, wherein:

4 the device end face includes an outwardly protruding portion extending along the  
5 substrate from a bottom portion of the device end face beneath a proximal  
6 portion of the end-coupled waveguide; and

7 at least one layer of the end-coupled waveguide decreases in thickness toward the  
8 end face, the outwardly protruding portion of the device waveguide and the  
9 decreasing layer thickness together yielding a desired layer surface profile for at  
10 least one layer of the end-coupled waveguide.

11 63. The method of Claim 44, further comprising:

12 forming for the semiconductor optical device a second device waveguide segment  
13 terminating at a second device end face;

14 depositing waveguide cladding material on the substrate and the second device end  
15 face so that the cladding material substantially covers the device end face and  
16 forms a second waveguide lower cladding layer;

17 depositing waveguide core material over the second lower cladding layer so as to  
18 form a second waveguide core, deposited waveguide core material extending  
19 upward from a proximal end of the second waveguide core away from the  
20 substrate; and

21 depositing waveguide cladding material over the waveguide core material and  
22 second lower cladding layer so as to form a second waveguide upper cladding  
23 layer,

24 wherein the second lower cladding layer, second waveguide core, and second  
25 upper cladding layer form a second end-coupled planar optical waveguide on  
26 the device substrate end-coupled at its proximal end to the device waveguide  
27 through the second device end face.

28 64. A method, comprising:

1 forming a semiconductor optical device on a device substrate, the optical device  
2 including a device waveguide segment terminating at a device end face;  
3 depositing waveguide cladding material on the substrate so as to form a waveguide  
4 lower cladding layer;  
5 depositing waveguide core material over the lower cladding layer so as to form a  
6 waveguide core;  
7 depositing waveguide cladding material over the waveguide core material and the  
8 lower cladding layer so as to form a waveguide upper cladding layer, thereby  
9 forming an end-coupled planar optical waveguide on the device substrate end-  
10 coupled at its proximal end to the device waveguide through the device end  
11 face, the end-coupled waveguide comprising the lower cladding layer, the  
12 waveguide core, and the upper cladding layer; and  
13 forming a reflective coating between the device substrate and at least a portion of  
14 the end-coupled waveguide.

15 65. The method of Claim 64, wherein the reflective coating comprises a metallic  
16 coating.

17 66. The method of Claim 64, wherein the reflective coating comprises a dielectric  
18 coating.

19 67. The method of Claim 64, wherein the end-coupled waveguide comprises a low-  
20 index planar optical waveguide.

21 68. A method, comprising:

22 forming a semiconductor optical device on a device substrate, the optical device  
23 including a device waveguide segment terminating at a device end face;  
24 depositing waveguide cladding material on the substrate so as to form a waveguide  
25 lower cladding layer;  
26 depositing waveguide core material over the lower cladding layer so as to form a  
27 waveguide core;  
28 depositing waveguide cladding material over the waveguide core material and the  
29 lower cladding layer so as to form a waveguide upper cladding layer, thereby

1 forming an end-coupled planar optical waveguide on the device substrate end-  
2 coupled at its proximal end to the device waveguide through the device end  
3 face, the end-coupled waveguide comprising the lower cladding layer,  
4 waveguide core, and the upper cladding layer; and  
5 optically end-coupling a second optical waveguide with the end-coupled planar  
6 optical waveguide at a distal end thereof.

7 69. The method of Claim 68, wherein the second optical waveguide comprises an  
8 optical fiber, and further comprising mounting the optical fiber on the device  
9 substrate.

10 70. The method of Claim 68, wherein the second optical waveguide comprises a planar  
11 optical waveguide formed on a waveguide substrate, and further comprising  
12 mounting the device substrate on the waveguide substrate.

13 71. The method of Claim 68, further comprising adapting the end-coupled waveguide  
14 for functioning as a transverse-mode expander.

15 72. The method of Claim 68, wherein the end-coupled waveguide comprises a low-  
16 index planar optical waveguide.

17 73. A method, comprising:

18 forming a semiconductor optical device on a device substrate, the optical device  
19 including a device waveguide segment terminating at a device end face;  
20 depositing waveguide cladding material on the substrate so as to form a waveguide  
21 lower cladding layer;  
22 depositing waveguide core material over the lower cladding layer so as to form a  
23 waveguide core;  
24 depositing waveguide cladding material over the waveguide core material and the  
25 lower cladding layer so as to form a waveguide upper cladding layer, thereby  
26 forming an end-coupled planar optical waveguide on the device substrate end-  
27 coupled at its proximal end to the device waveguide through the device end

1 face, the end-coupled waveguide comprising the lower cladding layer,  
2 waveguide core, and the upper cladding layer; and  
3 optically transverse-coupling a second optical waveguide with the end-coupled  
4 planar optical waveguide.

5 74. The method of Claim 73, wherein the second optical waveguide comprises a planar  
6 optical waveguide formed on a waveguide substrate, and further comprising  
7 mounting the device substrate on the waveguide substrate.

8 75. The method of Claim 73, further comprising adapting at least one of the end-  
9 coupled waveguide and the second waveguide for substantially adiabatic  
10 transverse-coupling therebetween.

11 76. The method of Claim 73, wherein the end-coupled waveguide comprises a low-  
12 index planar optical waveguide.

13 77. A method, comprising:  
14 forming a semiconductor optical device on a device substrate, the optical device  
15 including a device waveguide segment terminating at a device end face;  
16 depositing waveguide cladding material on the substrate so as to form a waveguide  
17 lower cladding layer;  
18 depositing waveguide core material over the lower cladding layer so as to form a  
19 waveguide core; and  
20 depositing waveguide cladding material over the waveguide core material and the  
21 lower cladding layer so as to form a waveguide upper cladding layer, thereby  
22 forming an end-coupled planar optical waveguide on the device substrate end-  
23 coupled at its proximal end to the device waveguide through the device end  
24 face, the end-coupled waveguide comprising the lower cladding layer,  
25 waveguide core, and the upper cladding layer,  
26 wherein at least a portion of the device end face is curved in at least one dimension.

27 78. The method of Claim 77, wherein the curved portion of the end face is convex.

- 1 79. The method of Claim 77, wherein the curved portion of the end face serves to  
2 increase reflective optical coupling of a device optical mode back into the device  
3 waveguide segment, relative to a substantially flat device end face.
- 4 80. The method of Claim 77, wherein the curved portion of the end face serves to  
5 increase optical end-coupling between the device waveguide segment and the end-  
6 coupled waveguide, relative to a substantially flat device end face.
- 7 81. The method of Claim 77, wherein the curved portion of the end face is limited in  
8 transverse extent so as to suppress higher-order device optical modes.
- 9 82. The method of Claim 77, wherein the end-coupled waveguide comprises a low-  
10 index planar optical waveguide.
- 11 83. A method, comprising:  
12 forming a semiconductor optical device on a device substrate, the optical device  
13 including a device waveguide segment terminating at a device end face;  
14 depositing waveguide cladding material on the substrate so as to form a waveguide  
15 lower cladding layer;  
16 depositing waveguide core material over the lower cladding layer so as to form a  
17 waveguide core; and  
18 depositing waveguide cladding material over the waveguide core material and the  
19 lower cladding layer so as to form a waveguide upper cladding layer, thereby  
20 forming an end-coupled planar optical waveguide on the device substrate end-  
21 coupled at its proximal end to the device waveguide through the device end  
22 face, the end-coupled waveguide comprising the lower cladding layer,  
23 waveguide core, and the upper cladding layer,  
24 wherein:  
25 the device end face includes an outwardly protruding portion extending along the  
26 substrate from a bottom portion of the device end face beneath a proximal  
27 portion of the end-coupled waveguide; and  
28 at least one layer of the end-coupled waveguide decreases in thickness toward the  
29 end face, the outwardly protruding portion of the device waveguide and the

1 decreasing layer thickness together yielding a desired layer surface profile for at  
2 least one layer of the end-coupled waveguide.

3 84. The method of Claim 83, wherein a lower cladding layer of the end-coupled  
4 waveguide decreases in thickness toward the end face, the outwardly protruding  
5 portion of the device waveguide and the decreasing lower cladding layer thickness  
6 together yielding a substantially flat upper surface of the lower cladding layer above  
7 the protruding portion of the device waveguide.

8 85. The method of Claim 83, wherein a lower cladding layer of the end-coupled  
9 waveguide decreases in thickness toward the end face, the outwardly protruding  
10 portion of the device waveguide and the decreasing lower cladding layer thickness  
11 together serving to position a proximal end of a core of the end-coupled waveguide  
12 for optical end-coupling with the optical device.

13 86. The method of Claim 83, wherein the end-coupled waveguide comprises a low-  
14 index planar optical waveguide.  
15